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Temporal and spatial variations in consumption-based carbon dioxide emissions in China

Yanxia Zhang [a], Haikun Wang [a,b,c,*], Sai Liang [d], Ming Xu [d,e], Weidong Liu [f], Shalang Li [a], Rongrong Zhang [a], Chris P. Nielsen [c], Jun Bi [a,b,*]

[a] State Key Laboratory of Pollution Control and Resource Reuse, School of the Environment, Nanjing University, Nanjing 210023, PR China
[b] Institute for Climate and Global Change Research, Nanjing University, Nanjing 210093, PR China
[c] Harvard China Project, School of Engineering and Applied Sciences, Harvard University, 29 Oxford St, Cambridge, MA 02138, USA
[d] School of Natural Resources and Environment, University of Michigan, Ann Arbor, MI 48109-1041, USA
[e] Department of Civil and Environmental Engineering, University of Michigan, Ann Arbor, MI 48109-2125, USA
[f] Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, PR China

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ABSTRACT

China's CO_2 emissions have sharply increased in recent years with soaring economic development and urbanization. Consumption-based accounting of CO_2 emissions could provide new insights for allocating regional mitigation responsibility and curbing the emissions. A multi-regional input–output model is used to study the trends and disparities of consumption-based emissions from Chinese provinces during the period 2002–2007. Results show that China's consumption-based CO_2 emissions grew from 3549 Mt in 2002 to 5403 Mt in 2007 with an annual average growth rate of 8.8%. The annual growth rate in the richer eastern region was over 10% because of a rapid increase in capital investment and the growth of urban consumption. Consumption-based CO_2 emissions embodied in interprovincial trades contributed only 10% (351 Mt) to the national total of such emissions in 2002, but 16% (864 Mt) in 2007. Given low per capita emissions currently, China's consumption-based emissions have much room to grow because of further development of urbanization and stimulation of domestic demand. The government should pay greater attention to controlling CO_2 emissions from a consumption-based perspective.

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* Corresponding authors at: State Key Laboratory of Pollution Control and Resource Reuse, School of the Environment, Nanjing University, Nanjing 210023, PR China. Tel./fax: +86 25 89680533.
E-mail addresses: wanghk@nju.edu.cn (H. Wang), jbi@nju.edu.cn (J. Bi).

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1. Introduction

China has become the largest global CO_2 emitter in terms of emissions [1], and the second largest CO_2 emitter according to consumption-based accounting [2]. Before the Copenhagen United Nations climate change conference in December of 2009, the Chinese government committed to reduce CO_2 emission per unit of gross domestic product (GDP) in 2020 by 40–45% below the 2005 level according to production-based CO_2 accounting [3]. Consistent with this commitment, in January of 2012 China's State Council issued the 12th Five Year Plan that included controls on GHG emissions. It required a reduction in CO_2 emissions per unit of GDP (or emissions intensity) of 17% from 2010 to 2015, allocating the national target down to 31 provinces. However, given that China shows a large positive net export goods [2] and an increasing improvement of urbanization [4], both production-based and consumption-based CO_2 emissions have been increasing rapidly for the last decade [2]. China's CO_2 mitigation efforts should consider both production and consumption perspectives to realize these targets [5,6].

Prior studies have investigated national consumption-based CO_2 emissions by treating China as a homogeneous national entity [2]. However, China is a vast country with substantial regional variations in physical geography, economic development, infrastructure, population density, and lifestyles [7,8]. There are in particular pronounced differences in economic structure, available technologies, energy characteristics and consumption levels among the well-developed eastern provinces and the less-developed central and western provinces [4], resulting in large inter-provincial trade transfers of energy and other goods. This leads to large variations in consumption-based emissions among China's provinces. It is crucial to analyze consumption-based CO_2 emissions at the provincial level to support the implementation of provincial-level environmental policies [9], as well as the allocation of national CO_2 mitigation targets to the various provinces.

An environmental input–output (EIO) model is commonly used to analyze the embodied CO_2 emissions in trade [10]. Fundamental concepts and theories of input–output (IO) analysis can date back to Leontief's development in the 1930s [11], which has been applied to describe and analyze economic environmental relationships since the 1960s [12]. The main idea of this method is to extend the IO model by multiplying CO_2 emissions factor which can be regard as a satellite account. This technique has been widely used to assess carbon leakage issues at the global [2], national [5,13,14], and provincial level [7,15,16].

Following the compilation of China's multiregional input–output (MRIO) models for 2002 and 2007 [17,18] as well as single-regional IO tables for Chinese provinces for the same years, scholars have analyzed provincial CO_2 emissions embodied in international and interprovincial trade based on the local production chain [7], driving forces identified by structural decomposition analysis [4,19–21], and inter-regional CO_2 emission spillover [8,22]. However, systematic analyses of the temporal and spatial variations in consumption-based CO_2 emissions in China have not been conducted. Such analyses can identify emission features and the factors influencing consumption-based CO_2 emissions at the regional level, better informing China's CO_2 emission mitigation policies.

In this paper, we used China's 30-province MRIO models in 2002 and 2007 to show the changing trends and disparities among provincial consumption-based emissions, including those embodied in interprovincial trade, emission intensities, and per capita emissions. The results of this study provide compelling evidence for policy makers to manage consumption patterns in order to establish effective CO_2 mitigation policies.

2. Methodology and data

Provincial consumption-based CO_2 emissions are composed of emissions from local product consumption, interprovincial and international imports, and direct household energy consumption. A provincial-level MRIO model was adopted to calculate each province's CO_2 emissions caused by local product consumption and interprovincial imports (i.e., domestic supply chains). Emissions embodied in international imports were previously reported to be relatively small for China [23]. This allows simplification of the calculations by adopting the Peters et al. [2] method of estimating each province's CO_2 emissions embodied in international imports (Appendix A in the Supplementary Content (SC)).

Direct household CO_2 emissions from cooking, heating, appliance use, and other activities have not usually been considered when applying input–output theory to calculate consumption-based emissions in previous studies [24]. However, these emissions roughly account for 5% of total CO_2 emissions from fossil fuel burning in China according to our calculations (Tables A.1 and A.2), and approximately 1% at the global level [25]. Therefore, CO_2 emissions from direct household energy consumption are included in our provincial consumption-based estimates, using the guideline of IPCC [26].

2.1. Provincial CO_2 emissions inventories

Provincial CO_2 emissions inventories include emissions from both fuel combustion and the calcination process of cement production. The emissions were calculated based on provincial rather than national level energy statistics [27,28], as these more closely represent energy consumption of each province in China [9]. IPCC recommended approaches were adopted to calculate CO_2 emissions by economic sector.

In calculating CO_2 emissions from energy usage by sectors, we avoid double counting by eliminating transformation of energy in coke making, oil refining, coal cleaning, gas processing and coal products processing. The emission factor for each energy type was adopted from the localized values recommended by IPCC [29,30]. More details of CO_2 emissions inventories of industrial sectors can be seen in Appendix B in the SC. Process emissions of CO_2 from cement production were calculated based on the volume of provincial clinker production [31,32], using the IPCC default value for the emissions factor. For more details, see our previous results [30].

2.2. Environmentally-extended MRIO model

Provincial MRIO models for 2002 [17] and 2007 [18] endogenously calculate not only output specific to one province, but also outputs from all other provinces that arise from interprovincial trade in intermediate products. The interprovincial MRIO model includes 30 provinces and municipalities (Tibet, Taiwan, Hong Kong, and Macao were not included here). All MRIO data are in current prices.

The provincial-level MRIO models have slightly different economic sector classifications for various years, with 21 sectors for 2002 and 30 sectors for 2007. The provincial energy consumption by economic sector for 2002 and 2007 were respectively integrated to match the sectors of the MRIO for these two years. To facilitate certain comparative analyses presented below, we further integrated the results for both years into 8 sectors (Tables A.3 and A.4).

The MRIO tables have a column called "others", which is regarded as an error term representing different data sources [14,33–36]. This error term is omitted in the calculations of output. Thus, the newly calculating output equals the sum of the intermediate flows and the final demand, and is used to normalize the MRIO and emissions data. Because the MRIO in 2002 is a competitive IO model, respectively including import values in intermediate input and final demand matrices, to independently account for the embodied emissions from domestic production, the import value for each item was removed according to the method of Weber et al. [37]. Further details of the MRIO model appear in Appendix C in the SC.

To calculate the provincial consumption-based CO_2 emissions from domestic supply chains, the MRIO model was environmentally extended by using CO_2 emissions per unit of economic output as a satellite account:

$$E_d^r = diag[F(I-A)^{-1}]\, y_{d-cons}^r \tag{1}$$

$$F = \begin{pmatrix} F^1 \\ F^2 \\ \vdots \\ F^m \end{pmatrix}^T \left[F^j = \begin{pmatrix} f_1^m \\ f_2^m \\ \vdots \\ f_n^m \end{pmatrix} \quad and \quad f_i^j = \frac{CE_i^j}{EO_i^j}, (i = 1 \ldots n; j = 1 \ldots m) \right] \tag{2}$$

where E_d^r is total consumption-based CO_2 emissions of province, r, from domestic supply chains; F is the row matrix of satellite account composed of f_i^m which is accounted by dividing CO_2 emissions (CE_i^j) of sector, i, with its' economic output (EO_i^j) in province, j. I is the identity matrix, and $(I-A)^{-1}$ is the *Leontief inverse matrix* [38]. More details about A appear in Appendix C in the SC. y_{d-cons}^r is the final consumption, including households (the sum of rural (rur) and urban (urb) households), government (gov) and capital investment (cap)). Domestic supply chains in each province, r, can be expressed as:

$$y_{d-cons}^r = \begin{pmatrix} y^{1r} \\ y^{2r} \\ \vdots \\ y^{mr} \end{pmatrix} = \begin{pmatrix} y_{rur}^{1r} + y_{urb}^{1r} + y_{gov}^{1r} + y_{cap}^{1r} \\ y_{rur}^{2r} + y_{urb}^{2r} + y_{gov} + y_{cap}^{2r} \\ \vdots \\ y_{rur}^{mr} + y_{urb}^{mr} + y_{gov}^{mr} + y_{cap}^{mr} \end{pmatrix} \tag{3}$$

where y^{rr} is the provincial final consumption that directly comes from local provincial products. Thus, the consumption-based emissions from domestic supply chains for a particular province consist of those resulting from household (urban and rural) consumption, government consumption, and capital formation. Moreover, each of these categories includes emissions embodied in local consumption of products from the same province, interprovincial imports, and international imports.

$$E^r = E_d^r + E_h^r \tag{4}$$

E_h^r is CO_2 emissions from the direct household energy consumption of province, r, which is from provincial CO_2 emissions inventories. Consequently, the consumption-based emissions for a particular province (E^r) in this paper equals to those resulting from domestic supply chains plus direct household energy consumption.

3. Results

3.1. Overall variations and provincial contributions

Consumption-based CO_2 emissions grew from 3549 Mt in 2002 to 5403 Mt in 2007, with an annual growth rate of 8.8%. This is slightly less than the growth rate of production-based CO_2 emissions at the national level (10.8% per year) (Table A.5). Such emissions increased in most provinces because of the rapid socio-economic development and improvement of living conditions during 2002–2007. In order to facilitate reporting and discussion of the results, the 30 Chinese provinces and municipalities are grouped into an eastern region (ER), central region (CR), western region (WR), and northeastern region (NER), according to their geographic position and levels of economic development (Fig. 1).

In the developed ER, consumption-based CO_2 emissions increased by more than 10% per year for most provinces from 2002 to 2007, including Jiangsu (increasing 135 Mt with an annual growth rate at 13%), Zhejiang (201 Mt, 22%), Shandong (240 Mt, 15%), and Guangdong (138 Mt, 11%). Comparable growth also occurred in rapidly developing provinces of other regions, such as Hubei (77 Mt, 10%), Hunan (79 Mt, 12%), Chongqing (39 Mt, 9%), and in populous provinces such as in Sichuan (106 Mt, 14%) and Henan (83 Mt, 8%) (Fig. 1 and Table A.5).

In contrast, the rates of growth of consumption-based CO_2 emissions were relatively small in economically lagging and sparsely populated provinces in the WR [7], with Qinghai and Gansu even showing negative growth (Fig. 1). Moreover, the absolute levels of consumption-based CO_2 emissions were very small in these provinces. Qinghai, for example, had the smallest consumption-based CO_2 emissions (27 Mt in 2007), about one twentieth that of Shandong in the ER, which had the largest such emissions (478 Mt in 2007) (Table A.5).

At the national level, the share of consumption-based CO_2 emissions from capital formation showed a slight decrease, from 50% of the total in 2002 to 49% in 2007. The share of CO_2 emissions from household (rural and urban) consumption slightly increased, from 31% to 32%. CO_2 emissions from government consumption accounted for approximately 7% of the national total, and those from direct household energy consumption and international imports accounted for the other 12% of emissions. The consumption-based CO_2 emissions caused by capital formation and household consumption are discussed in the following sections because of their great impacts on total consumption-based CO_2 emissions (Tables A.1and A.2).

3.1.1. Consumption-based CO_2 emissions caused by capital formation (CCEC)

CCEC increased by 868 Mt (47% of the total increment of the consumption-based CO_2 emissions) (Table A.6) because of the rapid expansion of capital formation in China during 2002–2007, increasing from 42% to 49% of total GDP. At the provincial level, the largest increases of CCEC occurred in the developed ER during this period, including Zhejiang (151 Mt, with an annual growth rate of 30%), Shandong (134 Mt, 15%), Jiangsu (112 Mt, 17%), Guangdong (78 Mt, 13%), and Beijing (33 Mt, 12%). Also, the relatively developed and populous provinces in other regions showed similarly large increases of the CCEC, such as Jilin (74 Mt, with an annual growth rate of 78%), Liaoning (44 Mt, 12%), Hubei (52 Mt, 15%), Jiangxi (36 Mt, 12%), Sichuan (72 Mt, 22%), and Henan (55 Mt, 10%) (Fig. 2a).

The construction and machinery & equipment (ME) sectors were the main causes of growth in provincial CCEC from 2002 to 2007 (Fig. 2b). This was due to China's policies to stimulate the domestic economy during the same period, particularly policies regarding land and credit. In contrast to other developed countries, China's capital formation policy mainly focuses on development of transportation

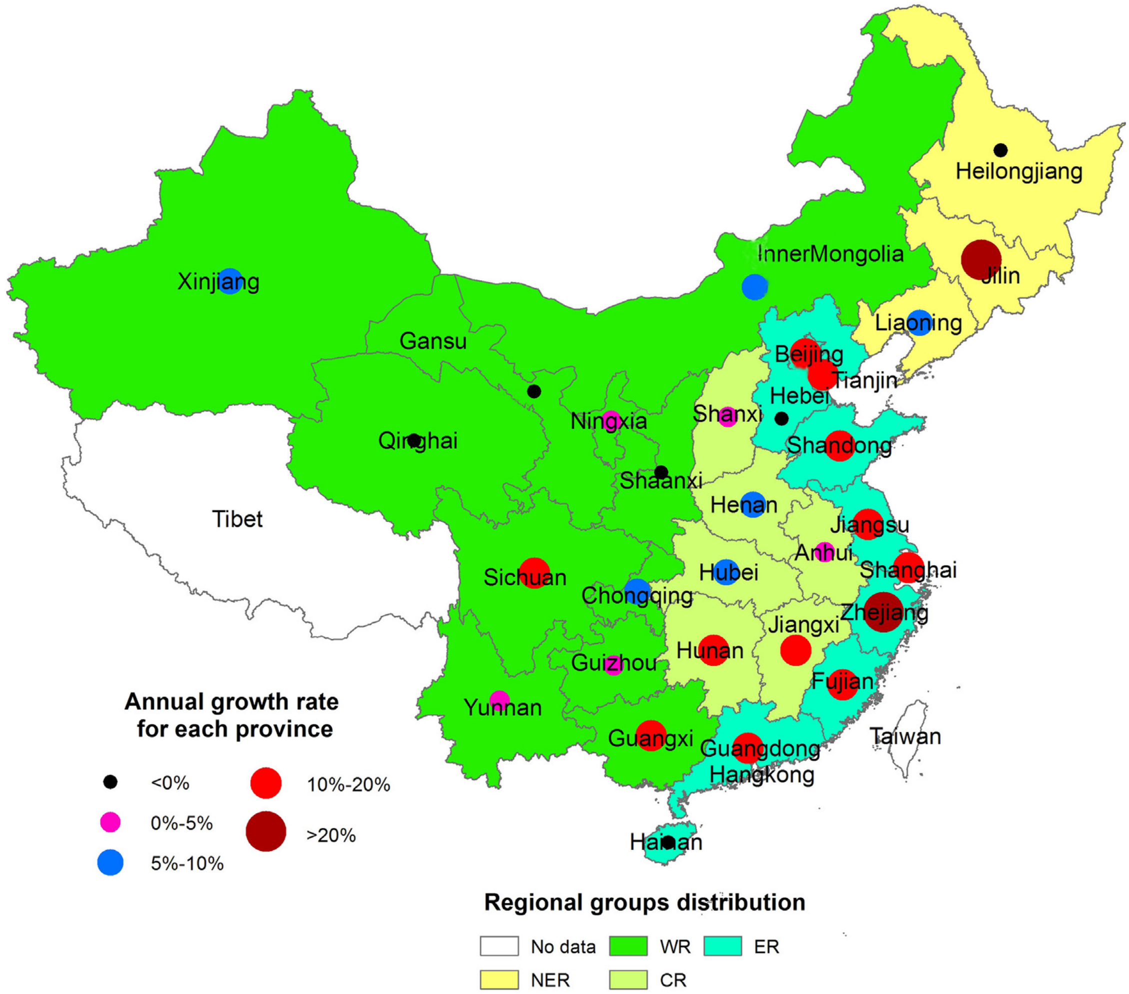

Fig. 1. Annual growth rate of consumption-based CO_2 emissions for each province during 2002–2007, the different colors of the map show the different regions.

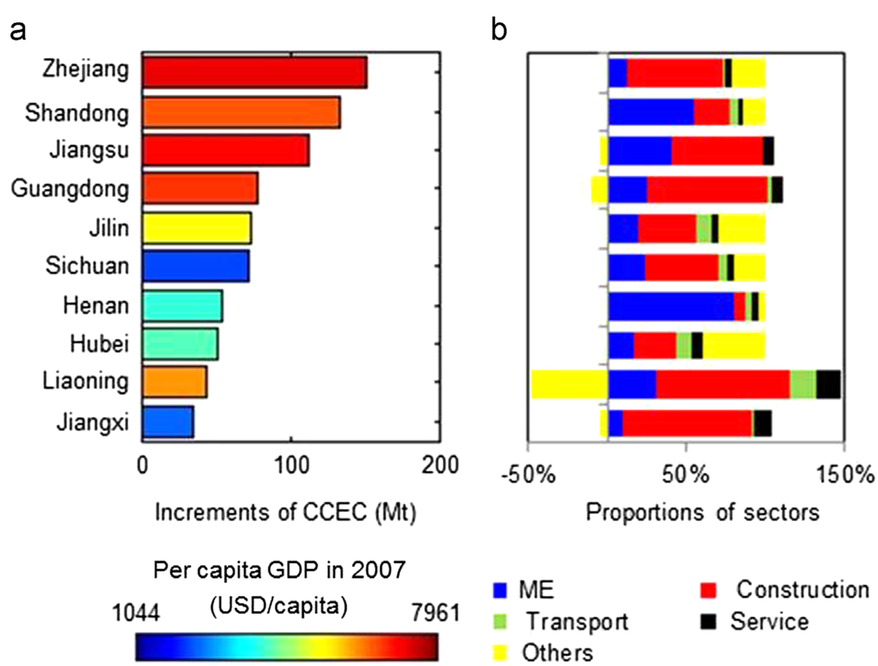

Fig. 2. The 10 provinces with the largest increments of consumption-based CO_2 emissions caused by capital formation (CCEC) from 2002 to 2007: (a) size of the emission increments, color-coded by per capita gross domestic product with relatively rich provinces in red and relatively poor ones in blue; (b) sector shares of the incremental CCEC.

infrastructure (e.g., rail and metro projects) and commercial construction, both of which use a lot of energy-intensive materials such as steel and cement, resulting in high CO_2 emissions. Capital investment in service industries, such as information technology and real estate, accounted for a relatively small share of the total increment of CCEC from 2002 to 2007.

3.1.2. Consumption-based CO_2 emissions caused by household consumption (CCEH)

CCEH contributed more than 30% to total consumption-based CO_2 emissions during 2002–2007 (Tables A.1 and A.2). However, consumption-based CO_2 emissions caused by rural consumption (CCER) decreased for most provinces because of rapid rural-to-urban migration as part of larger urbanization trends in China since 2000 [39] (Tables A.6 and A.1). Accordingly, China's urban population has expanded from 39% to 45% of the national population and per capita consumption increased from 892 USD to 1558 USD during the period 2002–2007 [40,41]. This leads to an increase in consumption-based CO_2 emissions caused by urban consumption (CCEU) of 737 Mt, which contributed 40% to the total increase of consumption-based CO_2 emissions (Table A.6).

The rich and developed eastern coastal provinces showed the largest increases of CCEU, such as Guangdong, Shandong, Shanghai, Zhejiang, Hebei, and Tianjin. For example, the CCEU of Guangdong reached 110 Mt in 2007, which is almost 5 times that in 2002 (23 Mt). The same phenomenon is found in many upper-medium income provinces in the central economic zones, such as in Hunan and Hubei (Fig. 3).

CCEU for most provinces resulted mainly from sectors closely linked with people's livelihood, such as consumption of food, clothing, electricity, heating, gas, and other household services. The food share of the total CCEU was relatively stable from 2002 to 2007, and share for textiles and clothing even decreased a little in most Chinese provinces. In contrast, the combined share for electricity, heating, gas, and water (EHGW) of the total CCEU increased. For example, in Chongqing, the share of emissions for textiles and clothing of total CCEU decreased from 19% to 7% from 2002 to 2007, while the share for EHGW-related emissions increased from 7% to 22% (Fig. 4). This

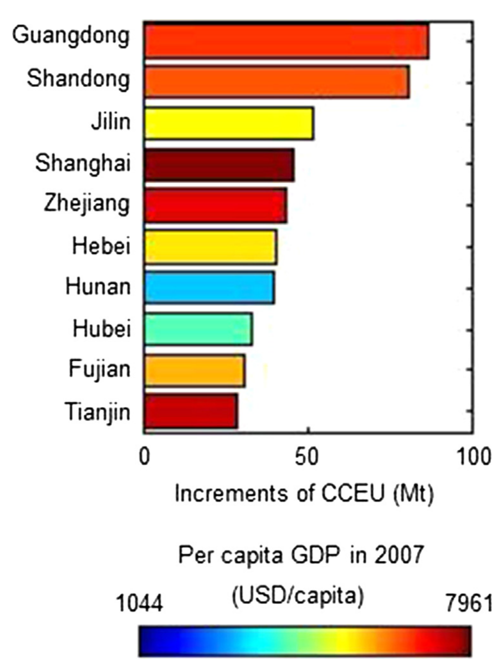

Fig. 3. The 10 provinces with the largest increments of consumption-based CO_2 emissions caused by urban consumption (CCEU) from 2002 to 2007, color-coded by per capita gross domestic product.

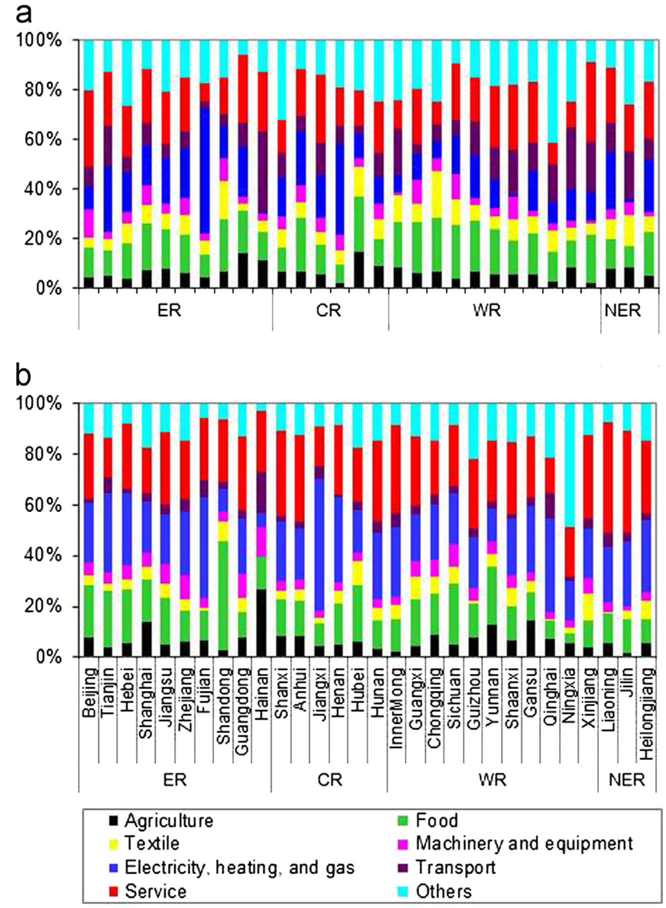

Fig. 4. Contributions of sectors to consumption-based CO_2 emissions caused by urban consumption (CCEU) in 2002 and 2007.

was not solely due to the rapid growth in ownership and use of energy- and water-consuming appliances, but also from indirect EHGW use through the production of other consumer items [4].

Due to the increase of urban consumption of services such as education, culture, health, travel, sports, and similar activities, the proportion of consumption-based CO_2 emissions caused by service industries rapidly increased within the total CCEU from 2002 to 2007 in most provinces. This is especially true in the less-developed but energy-abundant provinces, such as Shanxi (from 13% to 34%), Inner Mongolia (from 11% to 34%), and Anhui (from 18% to 34%). Although the shares of total CCEC due to emissions from the service sector kept stable in some developed municipalities during the period 2002–2007, the absolute amount of consumption-based CO_2 emissions caused by service sectors increased greatly, such as in Shanghai (from 6 Mt to 13 Mt) (Fig. 4).

3.2. Inter-provincial movement of consumption-based CO_2 emissions

The share of provincial consumption-based CO_2 emissions due to consumption of goods and services produced within the same province decreased from 79% (2785 Mt) in 2002 to 72% (3907 Mt) in 2007. Correspondingly, only 10% (351 Mt) of total consumption-based CO_2 emissions were embodied in inter-provincial trade in 2002, and grew to 16% (864 Mt) in 2007 (Tables A.7 and A.8). For a sense of comparative scale, note that this increment is roughly equivalent to the annual CO_2 emissions of Canada, the world's eighth largest production-based emitter [1] (Table A.9). Among the total increment of consumption-based CO_2 emissions transfer, CCEC embodied in interprovincial trade increased by 255 Mt (29% of the total increment

of CCEC), and CCEU embodied in interprovincial trade increased by 233 Mt (32% of the total increment of CCEU).

Highly developed municipalities, like Shanghai and Tianjin, have shown that almost all increases of CCEC came from interprovincial imports, especially from nearby provinces. For example, the increments of CCEC in Shanghai were mainly from Zhejiang (11%) and Anhui (14%) in 2007 (Table A.10). Some less-developed provinces in the WR, such as Ningxia, Guizhou, Yunnan, and Xinjiang, showed similar phenomena as the highly developed municipalities (Fig. 5a), although the total amount of CCEC increments were small. This was caused by the fact that industrial technologies in these provinces remained largely outmoded, and meeting demand for capital investment goods from local sources was difficult.

In contrast, only small shares of the increments of CCEC embodied in interprovincial imports occurred in the richer eastern provinces, which have stronger production capacities in manufacturing industries (e.g., machinery and equipment). For example, less than 1% of the increases to total CCEC in Zhejiang (768 t) and Shandong (982 t) were caused by interprovincial imports. Similar situations were seen in fast-developing and energy-rich provinces in other regions, like Jiangxi, Hubei, Jilin, Chongqing, and Sichuan (Fig. 5b). In Fig. 5b, the share of inter-provincial import to the total increment of CCEC was negative from 2002 to 2007 in Jiangxi. It is because the increment of CCEC embodied in inter-provincial import was a negative value, and the total increment of CCEC was a positive value (Fig. A.2).

The increments of CCEU from 2002 to 2007 were mainly embodied in interprovincial imports in China's municipalities, including Beijing (60%), Tianjin (85%), Shanghai (84%), and Chongqing (52%). For less-developed provinces in the WR, like Xinjiang, Shaanxi, Gansu, and Qinghai, the shares of the increments to CCEU from interprovincial imports were more than 40% because of outmoded commodities manufacturing coupled with demands associated with rapid urbanization (Fig. 5c). In contrast, relatively wealthy and resource-rich provinces like Hunan, Hubei, Liaoning, and Inner Mongolia showed only small shares of increments in CCEU from interprovincial imports (Fig. 5d).

3.3. Levels of provincial consumption-based CO_2 emissions

Consumption-based CO_2 emissions intensities (emissions per unit of GDP) sharply decreased in all regions from 2002 to 2007. Despite the smallest decrease rates in provinces of the ER, consumption-based CO_2 emission intensities were still much less than in other regions because of their higher GDPs and rapid improvements in production technologies [4]. Consumption-based CO_2 emissions intensities in the WR were greater than the developed regions, but had a much higher rate of decrease (declining 48% in five years). For example, Ningxia (in the less-developed WR) showed the highest consumption-based carbon intensity in 2007 (4.1 kg/USD), which was about five times that of Guangdong (0.8 kg/USD) in the developed ER (Table 1). Nevertheless, even in the most energy-efficient province of Guangdong, consumption-based CO_2 emissions intensity was still much higher than that of developed countries such as Japan (0.34 kg/USD) and the UK (0.26 kg/USD) [2].

The per capita consumption-based CO_2 emissions increased rapidly for most provinces from 2002 to 2007. The ER showed the

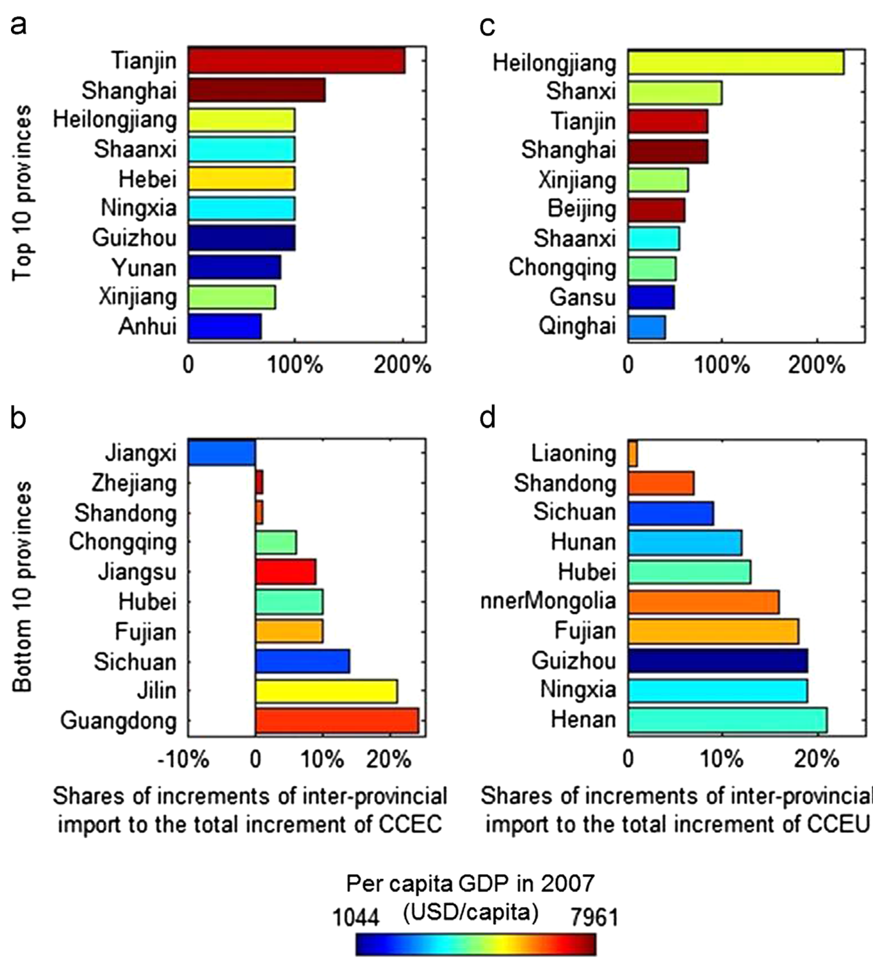

Fig. 5. The top 10 (upper panels) and bottom 10 (lower panels) provinces sorted by share of the increment of consumption-based CO_2 emissions embodied in inter-provincial imports to the total increment of consumption-based CO_2 emissions caused by capital formation (CCEC) ((a) and (b)), and by urban consumption (CCEU) ((c) and (d)), color-coded by per capita gross domestic product.

Table 1
Consumption-based CO_2 emissions intensity and per capita CO_2 emissions at provincial level in 2002 and 2007.

Regions	Provinces	Consumption-based CO_2 emissions intensities (kg/$)			Consumption-based CO_2 emissions per capita (t/capita)		
		2002	2007	Growth (%)	2002	2007	Growth (%)
Eastern region (ER)	Beijing	2.08	1.39	−33.2	7.65	11.02	44.1
	Tianjin	2.70	1.68	−37.7	6.96	10.41	49.7
	Hebei	3.68	1.32	−64.2	3.97	3.40	−14.5
	Shanghai	2.44	1.74	−28.8	9.88	13.82	39.9
	Jiangsu	1.32	0.89	−32.6	2.28	3.94	72.6
	Zhejiang	1.20	1.29	7.1	2.43	6.15	153.1
	Fujian	1.14	1.03	−9.9	1.78	3.47	95.3
	Shandong	1.92	1.41	−26.5	2.62	5.10	94.7
	Guangdong	1.22	0.81	−34.0	2.26	3.49	54.7
	Hainan	6.65	1.57	−76.5	6.22	3.06	−50.9
	Mean	**1.89**	**1.26**	**−33.4**	**3.32**	**5.31**	**59.9**
Central region (CR)	Shanxi	5.85	2.52	−56.9	4.99	5.89	18.0
	Anhui	3.17	1.70	−46.4	2.20	2.69	22.5
	Jiangxi	3.09	2.21	−28.5	2.17	3.86	78.1
	Henan	2.45	1.32	−46.0	1.86	2.79	50.2
	Hubei	2.60	1.71	−34.3	2.33	3.67	57.7
	Hunan	2.16	1.51	−30.2	1.63	2.94	80.3
	Mean	**2.89**	**1.64**	**−43.2**	**2.22**	**3.24**	**45.5**
Western region (WR)	Inner Mongolia	4.57	2.04	−55.4	4.49	7.09	57.7
	Guangxi	2.18	1.49	−31.6	1.38	2.40	73.7
	Chongqing	2.90	1.77	−39.1	2.48	3.86	55.7
	Sichuan	1.98	1.58	−20.3	1.39	2.69	93.5
	Guizhou	5.49	2.75	−49.8	2.15	2.88	33.9
	Yunnan	3.31	1.81	−45.3	2.13	2.51	18.0
	Shaanxi	4.26	1.48	−65.2	3.17	3.03	−4.4
	Gansu	5.71	2.13	−62.8	3.36	2.96	−11.7
	Qinghai	7.39	2.62	−64.6	5.75	4.97	−13.6
	Ningxia	9.81	4.10	−58.2	7.82	8.12	3.9
	Xinjiang	3.36	1.96	−41.6	3.44	4.34	26.2
	Mean	**3.42**	**1.77**	**−48.2**	**2.39**	**3.18**	**32.9**
Northeastern region (NER)	Liaoning	2.20	1.54	−30.0	3.44	5.25	52.5
	Jilin	2.09	2.73	30.6	2.19	6.94	216.4
	Heilongjiang	4.84	2.19	−54.8	5.58	5.35	−4.1
	Mean	**2.93**	**1.83**	**−37.5**	**3.79**	**5.23**	**38.1**
Total	**Total**	**2.44**	**1.47**	**−39.7**	**2.79**	**4.15**	**48.7**

largest rate of increase (growing 60% in five years), while the WR had the smallest (33%) over the same period. For developed municipalities in the ER, such as Beijing, Tianjin, and Shanghai, their per capita consumption-based CO_2 emissions ranging from 11.0 to 13.8 t/capita were already comparable to the Japanese level (11.7 t/capita) in 2007 [2] (Table 1).

For most developing and energy-scarce provinces in the CR and WR, the per capita consumption-based CO_2 emissions were still very small in 2007. For example, Guangxi (in the less-developed WR) showed the lowest per capita consumption-based CO_2 emissions (2.4 t/capita), only one sixth that of Shanghai. However, in energy-rich central and western provinces, the per capita consumption-based CO_2 emissions were relatively high, such as in Shanxi (5.9 t/capita) and Inner Mongolia (7.1 t/capita). This is due to rapid increases of coal consumption to support large-scale urbanization and industrialization in these provinces [42].

4. Policy implications

4.1. Transforming the direction of capital investment

Increases of capital consumption-based CO_2 emissions were mainly caused by the growth of consumption of construction and ME, which are both CO_2-intensive sectors from a life-cycle perspective. To control the growth of CO_2 emissions from consumption of capital goods and services, government should set a series of policies to alter conventional capital investment practices. For example, a carbon tax could be gradually implemented according to different economic development and industry characteristics in various provinces, with national coordination [43].

Given the relatively advanced state of transportation and other infrastructure systems in China's developed municipalities, it is necessary to mitigate CO_2 emissions from capital consumption by reducing demands for steel, cement, and ME. For example, the capital investment could be shifted to high-technology IT applications, new energy development, education, and other lower-carbon industries, instead of investing in more road and real estate construction projects. Due to the advantages of manufacturing technologies in some developed provinces of the ER, it will be useful to shift from traditional high-CO_2-emiting manufacturing industries (e.g., textiles, paper, and ME) to strategic emerging industries as proposed in China's 12th Five Year Plan (e.g., high-end equipment manufacturing and bio-industry).

4.2. Promoting green lifestyles

The most CO_2-intensive sectors of urban consumption shifted somewhat over the 2002–2007 period, from food and textiles to services and EHGW. This reflects that China's urban household consumption has increasingly reflected a more energy-intensive lifestyle afforded by higher incomes. For example, there were 95 air conditioners per 100 families among China's urban residents in 2007, and the number has already increased to 122 in 2011. Indeed

for urban residents living in the developed region of ER, there were 171 air conditioners per 100 families [41,44].

China's Eighteenth National People's Congress endorsed further development of urbanization and industrialization among the most important development orientations for the next decade. Therefore, there will be stronger demographic shifts, with people migrating from rural to urban areas and from the WR and CR to the coastal ER [45]. At the same time, economic policies seek to gradually shift from export-driven to consumption-led growth. Urban consumption CO_2 emissions are thus in keeping with expected increases in the future.

Therefore, it is crucial for China's government to guide the public towards sustainable lifestyle choices that can mitigate CO_2 emissions from urban consumption. For example, policy makers could adopt incentive measures (e.g., subsidies of energy-saving products [46]) to encourage the public to choose low-carbon products and public transportation. Moreover, carbon tax for some high-emission commodities could be imposed to restrict excessive consumption. For instance, it is reasonable to impose vehicle environmental taxes to control the rapid growth of the vehicle population and abate associated emissions [47].

4.3. Optimizing domestic CO_2 emission transfer

Consumption CO_2 emissions embodied in interprovincial trade increased by 531 Mt from 2002 to 2007. Large shares of the increments of consumption CO_2 emissions for this period were from interprovincial trade in highly developed municipalities (Fig. 5a and c). Because these cities face double pressures from rapid growth of local consumption and CO_2 emissions intensity targets that are higher than other parts of China, they transfer many energy-intensive industries to inland provinces where there are more energy reserves and lower population densities.

Nevertheless, relocation of energy and resource exploitation can result in resource optimization at the national level and directly stimulate economic development in less-developed regions by using relatively less energy and more advanced technologies. In other words, there is an efficiency gain in the current structure of production [48]. Actually, a cap and trade scheme has already been considered among some pilot provinces in China. A domestic clean development mechanism (CDM) would be developed so that participating provinces would be allowed to carry out some of their emissions reduction obligations in less-developed provinces and obtain carbon credits in return [49].

4.4. Sharing both production- and consumption-based responsibilities

Despite being the second ranking emitter of consumption-based CO_2, China's per capita consumption-based emissions in most provinces were still much lower than those of developed countries. For example, per capita CO_2 emissions were only 3.2 t in 2007 in the WR, just one fourth of the Japanese level. However, per capita consumption-based CO_2 emissions will inevitably increase in most provinces of China with continuing economic development, urbanization, and changes in lifestyles. Supposing China's per capital consumption CO_2 emissions were to increase to the level of Japan, this would be by nearly twice the current level. In that case, China would face tremendous pressures with regards both to energy demand and emissions reduction, and would likely become a net CO_2 emissions importer like US. This is untenable for the world and the climate. Thus, it is crucial to for China's government to work towards controlling CO_2 emissions from the consumption perspective.

5. Conclusions

The results reported here demonstrate that consumption-based CO_2 emissions rapidly increased in most provinces of China during 2002–2007. Given high economic growth and urbanization over the last decade, capital investment and urban consumption played primary roles in raising consumption-based CO_2 emissions. Therefore, it is essential to shift the capital investment orientation and to promote low-carbon consumption patterns of residents to control CO_2 emissions, but based on the distinctive features of provinces in terms of their economies, energy resources and consumption, and industrial capacities. Given more and more emissions transfer among provinces and/or regions to support local consumption, a cap-and-trade policy can be adopted among municipalities and their neighboring provinces to optimize the domestic CO_2 emission transfer at the national level from a consumption-based perspective.

In the future, more research is needed on the interactions among the supply chains of sectors within China, which will provide more accurate information about factors driving the increases of consumption-based CO_2 emissions. Currently, uncertainties from underlying MRIO and energy data contribute to uncertainties of the estimates of consumption-based CO_2 emissions for each province. Improving the social-economic data and energy statistics to provide more accurate data will help reduce this uncertainty. In addition, linking China's MRIO models (2002 and 2007) to a global MRIO model is advised, to reduce uncertainties concerning emissions imbedded in international imports.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.rser.2014.07.178.

References

[1] CDIAC (Carbon Dioxide Information Analysis Center). Ranking of the world's countries by 2010 total CO_2 emissions from fossil-fuel burning, cement production, and gas flaring. ⟨http://cdiac.ornl.gov/trends/emis/top2010.tot⟩; 2013.
[2] Peters GP, Minx JC, Weber CL, Edenhofer O. Growth in emission transfers via international trade from 1990 to 2008. Proc Nat Acad Sci USA 2011;108:8903–8.
[3] Wang Y, Liang S. Carbon dioxide mitigation target of China in 2020 and key economic sectors. Energy Policy 2013;58:90–6.
[4] Feng K, Siu YL, Guan D, Hubacek K. Analyzing drivers of regional carbon dioxide emissions for China a structural decomposition analysis. J Ind Ecol 2012;16:600–11.
[5] Peters GP. From production-based to consumption-based national emission inventories. Ecol Econ 2008;65:13–23.
[6] Peters GP, Hertwich EG. CO_2 embodied in international trade with implications for global climate policy. Environ Sci Technol 2008;42:1401–7.
[7] Guo Je, Zhang Z, Meng L. China's provincial CO_2 emissions embodied in international and interprovincial trade. Energy Policy 2012;42:486–97.
[8] Meng B, Xue J, Feng K, Guan D, Fu X. China's inter-regional spillover of carbon emissions and domestic supply chains. Energy Policy 2013;61:1305–21.
[9] Guan D, Liu Z, Geng Y, Lindner S, Hubacek K. The gigatonne gap in China's carbon dioxide inventories. Nat Clim Change 2012;2:672–5.
[10] Xu M, Li R, Crittenden JC, Chen YS. CO_2 emissions embodied in China's exports from 2002 to 2008: a structural decomposition analysis. Energy Policy 2011;39:7381–8.
[11] Leontief WW. Input–output economics. Oxford, UK: Oxford University Press; 1986.

[12] Chang YF, Lin SJ. Structural decomposition of industrial CO_2 emission in Taiwan: an input–output approach. Energy Policy 1998;26:5–12.

[13] Peters GP, Hertwich EG. Pollution embodied in trade: the Norwegian case. Global Environ. Change—Hum Policy Dimens 2006;16:379–87.

[14] Peters GP, Weber CL, Guan D, Hubacek K. China's growing CO_2 emissions a race between increasing consumption and efficiency gains. Environ Sci Technol 2007;41:5939–44.

[15] Wu LB, Kaneko S, Matsuoka S. Driving forces behind the stagnancy of China's energy-related CO_2 emissions from 1996 to 1999: the relative importance of structural change, intensity change and scale change. Energy Policy 2005;33:319–35.

[16] Guo S, Shao L, Chen H, Li Z, Liu JB, Xu FX, et al. Inventory and input–output analysis of CO_2 emissions by fossil fuel consumption in Beijing 2007. Ecol Inf 2012;12:93–100.

[17] Shi M, Zhang Z. Interprovincial input–output model and economy relationship in China. Beijing: Science Press; 2012.

[18] Liu W, Chen J, Tang Z. China's 30 provinces interprovincial input–output model theory and practice in 2007. Beijing: China Statistics Press; 2012.

[19] Chong WHB, Guan D, Guthrie P. Comparative analysis of carbonization drivers in China's megacities. J Ind Ecol 2012;16:564–75.

[20] Liang S, Zhang TZ. What is driving CO_2 emissions in a typical manufacturing center of South China? The case of Jiangsu Province Energy Policy 2011;39:7078–83.

[21] Wang YF, Zhao HY, Li LY, Liu Z, Liang S. Carbon dioxide emission drivers for a typical metropolis using input–output structural decomposition analysis. Energy Policy 2013;58:312–8.

[22] Feng K, Davis SJ, Sun L, Li X, Guan D, Liu W, et al. Outsourcing CO_2 within China. Proc Nat Acad Sci 2013;110:11654–9.

[23] Yan YF, Yang LK. China's foreign trade and climate change: a case study of CO_2 emissions. Energy Policy 2010;38:350–6.

[24] Qin Z. Research of China's population, consumption and carbon emissions. Shanghai: Fudan University Press; 2011.

[25] CDIAC (Carbon Dioxide Information Analysis Center). Global CO_2 emissions from fossil-fuel burning, cement manufacture, and gas flaring: 1751–2010. 〈http://cdiac.ornl.gov/trends/emis/top2010〉.tot; 2013.

[26] IPCC (Intergovernmental Panel on Climate Change). 2006 IPCC guidelines for national greenhouse gas inventories. Hayama: The Insitue for Global Environmental Strategies, Japan; 2006.

[27] PBS (Provincial Bureau of Statistics). Provincial statistical yearbooks, 2003. Beijing: China Statistics Press; 2003.

[28] PBS (Provincial Bureau of Statistics). Provincial statistical yearbooks, 2008. Beijing: China Statistics Press; 2008.

[29] Wang H, Zhang R, Liu M, Bi J. The carbon emissions of Chinese cities. Atmos Chem Phys 2012;12:6197–206.

[30] Liu M, Wang H, Wang H, ZhaoY TO, XH Y, et al. Refined estimate of China's CO_2 emissions in spatiotemporal distributions. Atmos Chem Phys 2013; 13:10873–82.

[31] CCA (China Cement Association). China cement almanac. Nanjing: Jiangsu Peoples Publishing, LTD; 2008.

[32] CCA (China Cement Association). China cement almanac. Nanjing: Jiangsu Peoples Publishing, LTD; 2003.

[33] Liang S, Liu Z, Xu M, Zhang T. Waste oil derived biofuels in China bring brightness for global GHG mitigation. Bioresour Technol 2013;131:139–45.

[34] Liang S, Xu M, Zhang T. Unintended consequences of bioethanol feedstock choice in China. Bioresour Technol 2012;125:312–7.

[35] Liang S, Xu M, Suh S, Tan RR. Unintended environmental consequences and co-benefits of economic restructuring. Environ Sci Technol 2013;47:12894–902.

[36] Liang S, Xu M, Liu Z, Suh S, Zhang T. Socioeconomic drivers of mercury emissions in China from 1992 to 2007. Environ Sci Technol 2013;47:3234–40.

[37] Weber CL, Peters GP, Guan D, Hubacek K. The contribution of Chinese exports to climate change. Energy Policy 2008;36:3572–7.

[38] Miller RE, Blair PD. Input–output analysis foundations and extensions. New York: Cambridge University Press; 2009.

[39] Jiang ZJ, Lin BQ. China's energy demand and its characteristics in the industrialization and urbanization process. Energy Policy 2012;49:608–15.

[40] NBSC (National Bureau of Statistics of China). China statistical yearbook, 2003. Beijing: China Statistics Press; 2003.

[41] NBSC (National Bureau of Statistics of China). China statistical yearbook, 2008. Beijing: China Statistics Press; 2008.

[42] NBSC (National Bureau of Statistics of China). China energy statistical yearbook, 2008. Beijing: China Statistics Press; 2008.

[43] Lo AY. Carbon emissions trading in China. Nat Clim Change 2012;2:765–6.

[44] NBSC (National Bureau of Statistics of China). China statistical yearbook, 2012. Beijing: China Statistics Press; 2012.

[45] Guan D, Hubacek K, Weber CL, Peters GP, Reiner DM. The drivers of Chinese CO_2 emissions from 1980 to 2030. Global Environ. Change—Hum Policy Dimens 2008;18:626–34.

[46] NDRC (National Development and Reform Commission). The "Energy saving products project" notification. 〈http://bgt.ndrc.gov.cn/zcfb/200905/t20090525_498145.html〉; 2009.

[47] Feng Y, Fullerton D, Gan L. Vehicle choices, miles driven, and pollution policies. J Regul Econ 2013;44:4–29.

[48] Yu X. Economic growth and resources constraints during low-carbon age. Resour Ind 2011;13:139–43.

[49] Lindner S, Liu Z, Guan D, Geng Y, Li X. CO_2 emissions from China's power sector at the provincial level: consumption versus production perspectives. Renewable Sustainable Energy Rev 2013;19:164–72.